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Fast Moment Magnitude Determination from P-wave Trains for Bucharest Rapid Early Warning System (BREWS)

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Abstract—Bucharest, with a population of approximately 2 million people, has suffered damage from earthquakes in the Vrancea seismic zone, which is located about 170 km from Bucharest, at a depth of 80–200 km. Consequently, an earthquake early warning system (Bucharest Rapid earthquake Early Warning System or BREWS) was constructed to provide some warning about impending shaking from large earthquakes in the Vrancea zone. In order to provide quick estimates of magnitude, seismic moment was first determined from P-waves and then a moment magnitude was determined from the moment. However, this magnitude may not be consistent with previous estimates of magnitude from the Romanian Seismic Network. This paper introduces the algorithm using P-wave spectral levels and compares them with catalog estimates. The testing procedure used waveforms from about 90 events with catalog magnitudes from 3.5 to 5.4. Corrections to the P-wave determined magnitudes according to dominant intermediate depth events mechanism were tested for November 22, 2014, M5.6 and October 17, M6 events. The corrections worked well, but unveiled overestimation of the average magnitude result of about 0.2 magnitude unit in the case of shallow depth event ($H < 60$ km). The P-wave spectral approach allows for the relatively fast estimates of magnitude for use in BREWS. The average correction taking into account the most common focal mechanism for radiation pattern coefficient may lead to overestimation of the magnitude for shallow events of about 0.2 magnitude unit. However, in case of events of intermediate depth of M6 the resulting M_w is underestimated at about 0.1–0.2. We conclude that our P-wave spectral approach is sufficiently robust for the needs of BREWS for both shallow and intermediate depth events.

Key words: Earthquake early warning system, spectral parameters, magnitude, Vrancea.

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1. Introduction

The main seismicity of Romania comes from the Vrancea region and is dominated by intermediate depth earthquakes occurring in a well-defined volume. The epicentral area is confined to about 40 km × 80 km (Fig. 1) and most earthquakes occur between 80 and 200 km depth within an almost vertical column (Marmureanu et al. 2008). Romania has experienced four strong Vrancea earthquakes (M_w 6.9–M_w 7.7) within the last 75 years. One of the biggest cities most affected by earthquakes in Romania is Bucharest, which is situated 140–170 km from the epicenter zone. Bucharest has experienced considerable damage due to the high-energy Vrancea intermediate depth earthquakes (Marmureanu et al. 2011). In 1977, an M_w 7.4 event was catastrophic when 35 high-rise buildings collapsed with 1500 causalities, the majority of them in Bucharest. To deal with this hazard in Bucharest, an earthquake early warning (EEW) system was proposed in 1999 (Wenzel et al. 1999) and is operated and developed by the National Institute for Earth Physics-Romania (NIEP) since 2002. The standard EEW approach uses the M_w calculations from the amplitudes of the recorded waves. The procedure uses the time interval of 25–30 s between the time when the P-wave is detected at the surface, in Vrancea epicentral area, and the arrival time of the dangerous S-wave at the site that needs to be protected. In the case of Bucharest, the system allows a warning time ranging between 25 and 30 s, depending on the depth of the events. In recent years, the seismic network in the Vrancea area has been upgraded with seismic equipment that allows rapid transmission of unsaturated strong motion data using 1 s data packets. At

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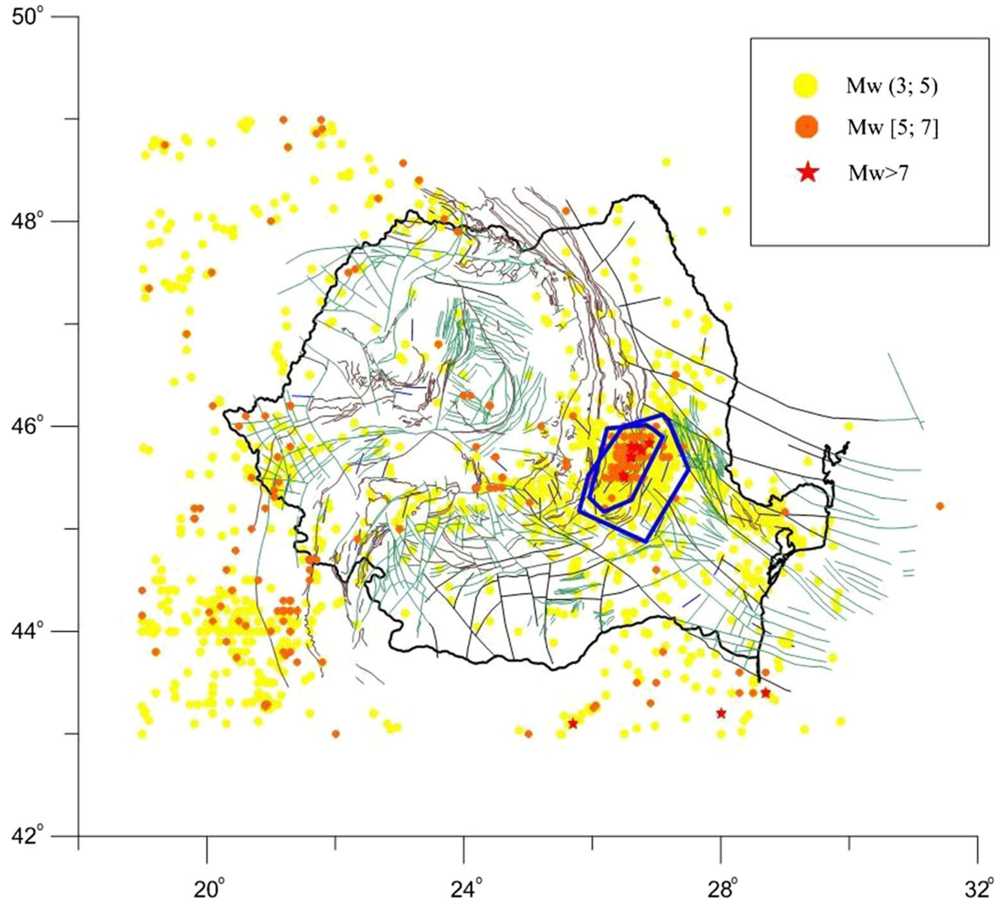

Figure 1
Seismicity of Romania and neighboring areas. Background of fundament and crustal faults (*black*), normal and strike-slip faults (*green*), accretion sedimentary faults (*brown*), probable crustal faults (*dotted line*). Vrancea intermediate depth seismic zone (*inner blue line*) and Vrancea crustal seismic zone (*outer blue line*) (BIGSEES project—Earthquake Catalog, http://infp.infp.ro/bigsees/Results.html)

the same time an improvement of the communication network has been carried out. It allows for redundant access to the real time data. The Early Warning System for Bucharest (BREWS) uses data from the stations deployed in the Vrancea area, which represent a subnetwork of the Romanian Seismic Network (RSN). The approach proposed in this work allows having the first M_w estimates before the S-waves hit the city. It is similar to the standard approach, but uses a different method. It can be used in parallel to the maximum peak of P-waves used in BREWS in the standard approach. Such double estimates may be further used in the decision-making process of the emergency state as a confirmation of properly issued alert. BREWS users tell us that a second method to get quick magnitude estimates would be a valuable addition. This paper is an attempt to fulfill this need.

Since the Vrancea region earthquakes occur in the depth range between 80 and 200 km, and the stations are placed in close epicentral distance from the source zone, the only method for fast spectral level determination was to use the P-wave trains. Because of the location of events the incident angle of the P-waves was steep and the data quality was very good. The algorithm of spectral level determination was based on up to 3 s boxcar window from the first P-wave arrival at the accelerometer stations. Then the FFT and spectrum were determined for displacement seismograms obtained by integration of original records. Upon well-known relation of Seismic

Moment and Spectral Level (e.g. Gibowicz and Kijko 1994) the estimates of M_0 were calculated and then, the estimates of M_w based on Hanks and Kanamori (1979) formula were also calculated. The estimates of M_w were obtained with spectral approach, then were compared with magnitudes from the Romanian catalog Romplus (http://www1.infp.ro/arhiva-in-timp-real), where M_w is computed from duration magnitude M_D (Oncescu et al. 1999). The latter magnitudes are the result of routine data processing and manually corrected before final publication in the catalog. This allowed checking the efficiency and accuracy of the method as well as its limitations. These correction factors for M_w estimations were prepared for the nearest to epicentral area stations assuming that the intermediate depth events have a common mechanism similar to the 1977, M7.4 event (Oncescu and Bonjer 1997). The P-wave spectral approach for magnitude estimation will allow for the relatively fast, additional determination of magnitude with use of the nearest stations. Such a method may be complementary for the routine magnitude determination in BREWS. This paper introduces the additional, fast M_w estimation routine, which allows comparing its results with the Romanian catalog magnitudes and routine BREWS estimates based on peak amplitude of P-waves. The spectral method corrected according to the most common focal mechanism is robust for the purpose of BREWS for both: intermediate depth events and shallow ones. The proposed method can be used parallel to the normal BREWS routine to check if there are no major discrepancies, which may influence the alerting procedure.

1.1. *Bucharest Rapid Early Warning System (BREWS) Part of the Romanian Seismic Network*

The Romanian Seismic Network (RSN) consists of 121 seismic stations in real time (short period or broadband collocated with strong motion acceleration sensors) and two arrays (Fig. 2). In the last years NIEP designed and extended a seismic sub-network in Bucharest (32 stations out of which 12 are in real time). All the real time stations stream 100 sps data for both 3-components acceleration and velocity sensors.

The large number of stations covers entirely the Romanian territory with a distance between them about 70 km in the north–west part and around 50 km in the east part. Toward the south part the seismic network is denser and the approximate distance between stations is 30 km. All of the data recorded by this network are transmitted in real time to the NIEP for automatic processing, analysis and dissemination. The RSN can be used also as an array at a bigger scale because of the large number of stations distributed on Romanian territory. The primary goal of the real time seismic network is to provide earthquake parameters for more rapid and accurate computation of the locations and magnitudes of earthquakes.

The present development of the seismic equipment and network, in case of strong events, allows rapid recording of unsaturated waveforms even in the epicentral area. Offline tests showed that a stable location using only P-detections can be obtained from a minimal number of six P-phase detections. The dense network together with the geometry caused by the depth of the events allows even 15 P-phases to arrive more or less in the same time in case of a 125 km depth event (Fig. 3). Figure 3 does not take into account the possible malfunctions of the communication network (Marmureanu et al. 2015).

Vrancea Earthquake Early Warning System (EEWS) uses the time interval of 25–30 s between the time when the “P” wave is detected at the surface, in Vrancea epicentral area, and the arrival time of the dangerous “S” wave at the site that needs to be protected. It uses four modules: (1) the local seismic network for detecting the P-wave, (2) two acquisition centers and computing facilities, (3) a redundant communication network, and (4) a warning distribution network to users.

Since September 2013, seven events in Vrancea with magnitude $M_w > 4.0$ have been recorded. All these events were detected by EWS and alerts were sent to 16 early warning receivers at the emergency response units located in Bulgaria and Romania: seven in Romania at Constanta, Calaraşi, Giurgiu, Teleorman, Dolj, Olt and Mehedinti and nine receivers in Bulgaria, at: Montana, Vidin, Veliko Tarnovo, Ruse, Belene, Dobrich, Kozlodui, Kozlodui 2 and Silistra.

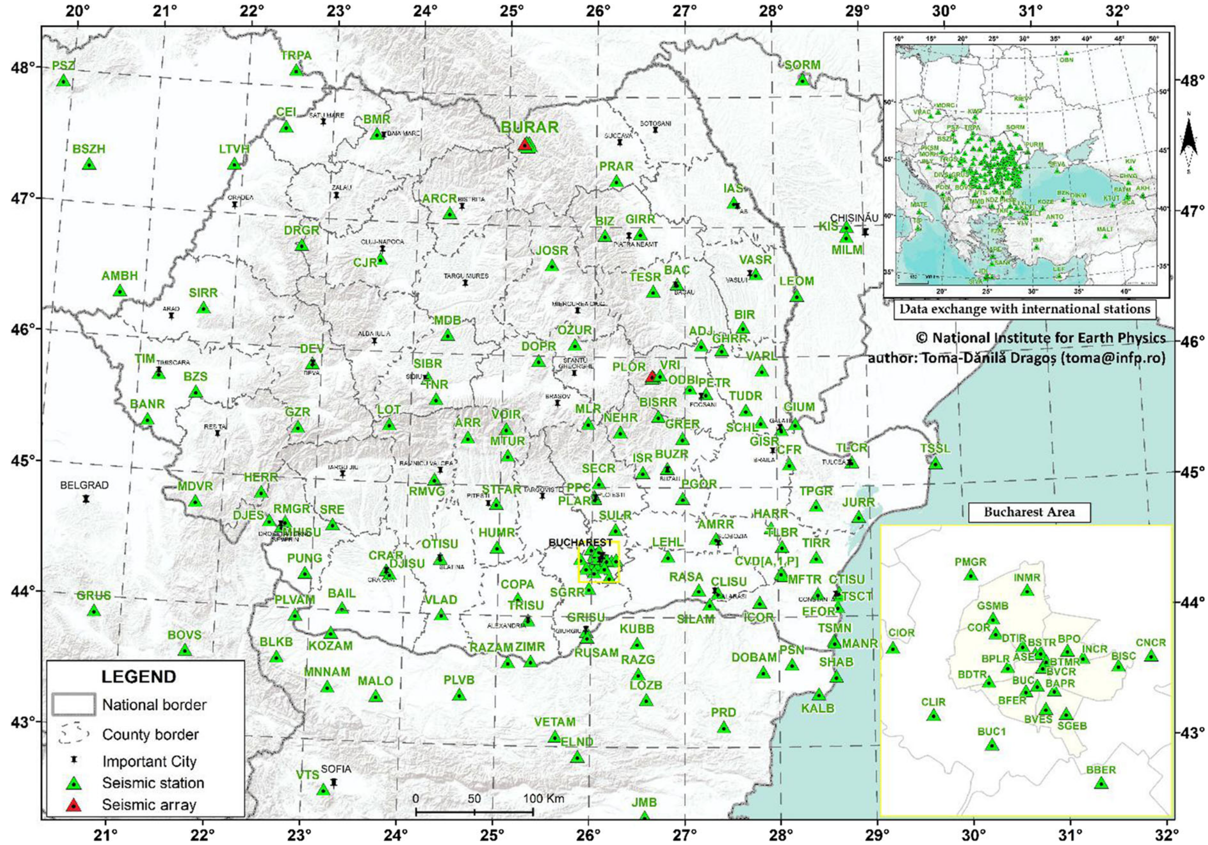

Figure 2
Romanian Seismic Network (February 2015) Modified from Toma-Danila (Toma-Danila 2012)

2. Methodology

Methodology of the M_w determination was based upon spectral level approximation (1) proposed by Andrews (1986):

$$\Omega_0 = 2\left(\frac{K^3}{J}\right)^{\frac{1}{4}}, \tag{1}$$

where J and K are according to Andrews (1986) and Snoke (1987):

$$J = 2\int_0^\infty V^2(f)\mathrm{d}f, \tag{2}$$

$$K = 2\int_0^\infty U^2(f)\mathrm{d}f, \tag{3}$$

where $U(f)$ and $V(f)$ are far-field ground displacement and velocity in frequency domain, respectively. The K was calculated upon Andrews (1986) approach. The calculations of K and J are influenced by the instrument response, sampling and noise; therefore, it is more practical to assume the limits of the instruments in calculation. The f_1 is an invert of the window length and is the lower frequency limit. The f_2, the high-frequency limit, is set to 10 Hz because at higher frequencies the signal and the noise are the same (Fig. 4). Before the application of the method in automated way, we performed manual tests on various signals and stations to check if the results are not influenced by the frequency band choice or the K estimation. The spectral level calculations based on (1) were stable when compared with manual inspection of the signal and spectra.

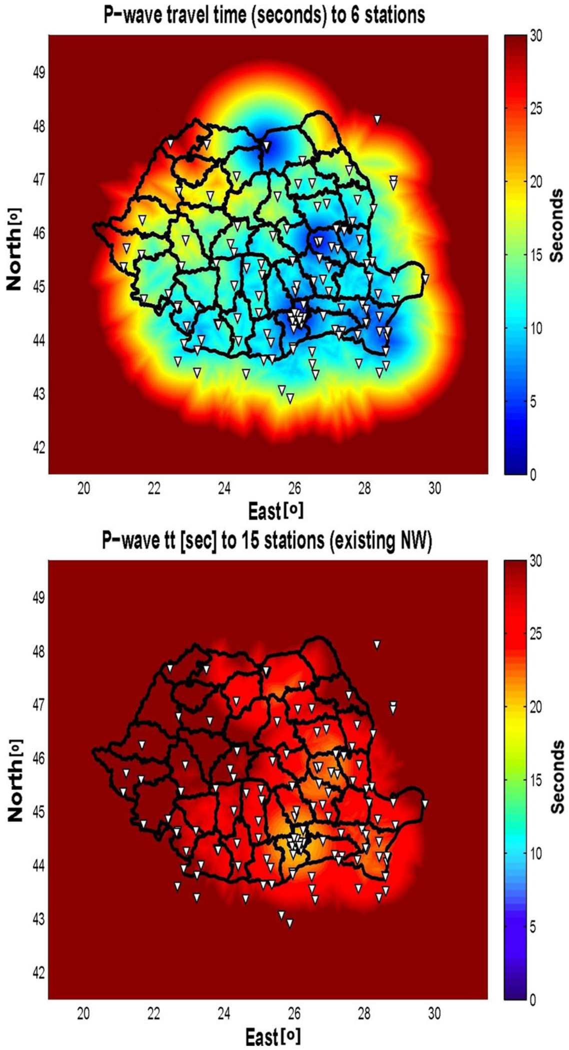

Figure 3
Theoretical P-wave travel time (seconds) to RSN from location to 6 stations for a 25 km depth event (*upper panel*) and P-wave travel time (seconds) to RSN from location to 15 stations for a 125 km depth event (*lower panel*)

Seismic moment was calculated upon Boore and Boatwright (1984) assumption of low-frequency level of the far-field displacement. Moment magnitude (4) (Hanks and Kanamori 1979) was estimated from seismic moment (5) M_0 [Nm] (Gibowicz and Kijko, 1994):

$$M_{\mathrm{w}} = \frac{2}{3}\log(M_0) - 6, \tag{4}$$

$$M_0 = \frac{4\pi\rho\alpha^3 R\Omega_0}{F_{\mathrm{c}} R_{\mathrm{c}} S_{\mathrm{c}}}, \tag{5}$$

where ρ is density of the source area, α is P-wave velocity in source, R is source-receiver distance, Sc is site correction, R_{c} free surface correction and F_{c} is P-wave radiation coefficient.

The analysis was performed using BREWS nearest station records. The closest stations' records of strong motion data (Q330 HR with 26 bits and Episensor acceleration sensor) were used. The main reason is that at big magnitude the velocity channels saturate. The relevant parts of accelerometric records of P-waves were selected upon auto-picking procedures used in BREWS with the 3 s time window. The data are double integrated in order to get displacement. The trend and mean removal from the accelerometer strong motion data was done before the instrument correction before the first integration. Then the resulting velocity signal was integrated to get displacement and one more time trend and mean were removed. Then displacement was transformed by Fast Fourier Transformation (FFT). The window was set to start about 0.2 s before the P-wave arrival picking to avoid missing the beginning of the wave train due to the picking inaccuracy. This may be the case when the automatic picking is enabled. There was no tapering used. The window size may be crucial in case of large earthquakes, but 3 s window used in this work covered well the P-wave trains for available data (Fig. 4). In the studied data, we did not notice any significant influence of the time window width on the spectral level estimates (Fig. 4). The spectral level values were stable for all used window lengths (from 3 to 8 s). The effects of longer windows and using Hamming and Hanning tapers were investigated and the only effect was changing the spectral level by about a factor of 2. The 3 s window was still a little longer than the P-wave train of M5.6 event (Fig. 4, uppermost panel). In case of larger events, there may be two possible drawbacks: first—the saturation of the signals on the closest stations, which is very unlikely, while the RSN stations are equipped with strong motion accelerometers, and second—too short window. Both these issues may provide underestimation of the magnitude. Having these issues in mind we decided to use the 3 s boxcar window length for the spectral level calculation, even though such window length for the M5.6 event is at

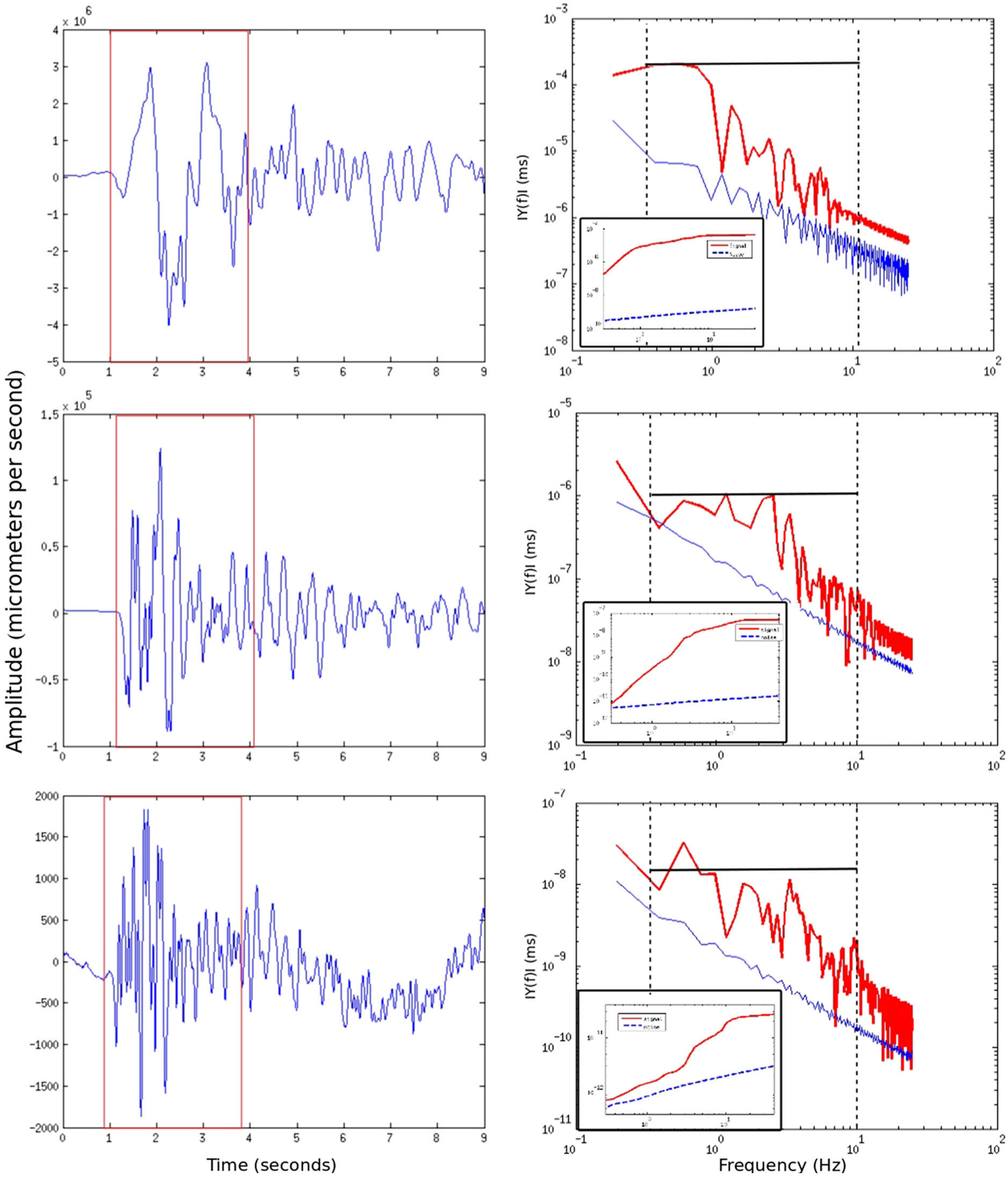

Figure 4
Examples of the spectral level estimates with the use of the 3 s window (*red rectangle* on the seismograms) and the 512 points FFT on MLR station for three different events: 22nd November 2014 M5.6 depth 39 km (*top panel*), 6th March 2006 M4.7 depth 152 km (*middle panel*), 11th May 2012 M3.8 depth 157 km (*bottom panel*). *Horizontal solid line* denotes the spectral level calculated upon (*1*), while *vertical dashed lines* denote the limits of the bandwidth used for analysis. *Blue line* on spectral plot denotes noise, while *red* one denotes P-wave train. Cumulative squared velocity plot of signal (*solid line*) and noise (*dashed line*) are shown in the *inserts*

the limit of the methodology. Unfortunately, there is only one M6 event with few recordings available to test the efficiency and the window length influence more extensively. Resulting amplitude spectra were corrected for attenuation effects with $Q = 400$ for P-wave. For further calculations we set velocities of P-waves in source at $V_P = 8100$ m/s for events located at depths below 112 km and 8000 m/s for events located at depths between above 112 km according to the local velocity model. Site correction and free surface correction were unknown for every station, therefore we set them as 1, while the F_c radiation coefficient was set as the P-wave coefficient calculated upon Ou (2008) for the assumed nodal plane orientation of the intermediate depth events taking into account the azimuth and take off angle. A total number of 1719 three-component strong motion recordings at 100 sps were used. There were 93 events from 2005 to 2012 with depth from 80 to 155 km (Fig. 5). Earthquakes occur in Vrancea at different depths. Between 60 and 80 (roughly) km depth there are no earthquakes. From 0 to 60 there are shallow events, from 80 km down there are intermediate depth events, that are the largest occurred in the area (e.g. 1802–$M_w = 7.8$, in the catalog is 150 km depth, 1977 event $M_w = 7.4$, the depth is 105 km). The shallow seismicity in the Vrancea

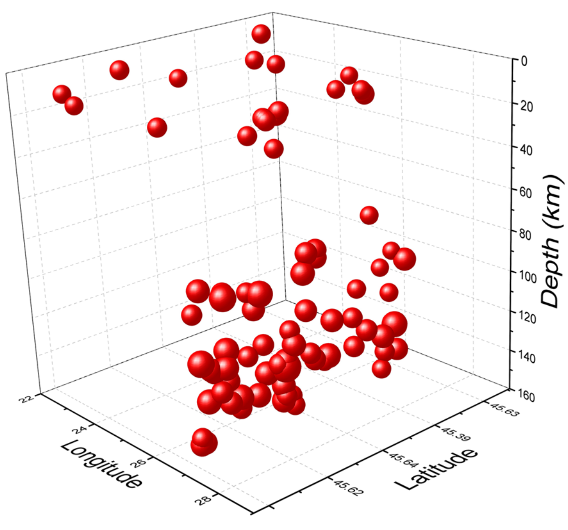

Figure 5
Spatial distribution of Vrancea region earthquakes (2005–2013). Only events with depth from 80 to 155 km were used in this study

region spreads eastward relative to the Carpathians arc bend, in the strip delimited by the Peceneaga-Camena fault to the north and Intramoesian fault to the south. Concerning the intermediate depth events there is a much peculiar idea. The Vrancea region is a complex seismic region of continental convergence characterized by three tectonic units in contact: the East European plate, Intra-Alpine and Moesian sub-plates. (Constantinescu et al. 1976). The subcrustal activity is concentrated at the bend of the Carpathian arc (Vrancea region) within a confined focal volume in the depth range from 80 to 200 km. It is rather clear that the most dangerous events in this zone are the events from the deeper part; therefore, only these events were taken for the study of the method robustness. Moreover, events from 80 km and deeper are more frequent than the shallow ones and the dominant mechanism of both groups differ (Craiu et al. 2016a). For intermediate depth, as a general rule they have reverse faulting, with nearly vertical tension (T) axis, and nearly horizontal pressure (P) axis. Regarding the nodal plane orientation, the two typical solutions evidenced by the earlier studies mentioned above—(1) nodal planes oriented mainly NE–SW and P-axis perpendicular to the Carpathian arc; and (2) nodal planes oriented mainly NW–SE and P-axis parallel to the Carpathian arc for instance one nodal plane of the 1977 had orientation 220°/76°/116° in terms of strike, dip and rake (Oncescu and Bonjer 1997; Craiu et al. 2016a). The upper part is characterized by various focal mechanisms—predominantly normal faulting, pointing out a complex stress field, characterizing the transition from the predominant compressive regime at depth to the extensional regime in the crust (Fig. 5).

The strategy of limiting the source-receiver stations with steep incident angle was chosen upon the observation of arrival time and the estimation results for randomly chosen events (Fig. 6). It is easily visible on Fig. 6, that the M_w estimates are stable up to about 30–35 degrees of incident angle. Influence of the incidence angle is both due to the surface correction and radiation pattern of the P-wave from the source according to the focal mechanism (Ou 2008). The radiation coefficients and free surface corrections were also applied due to known focal mechanism of this event. It stabilizes the results to

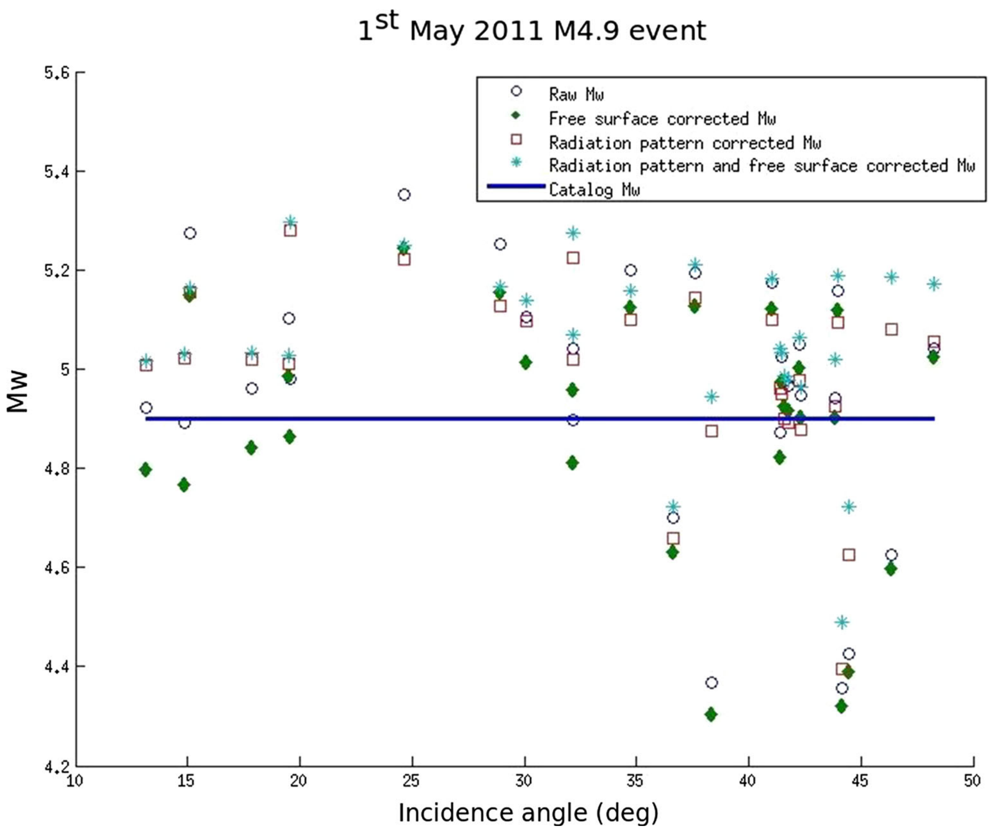

Figure 6
The example of the M_w estimations vs angle of the incidence for event of about 140 km depth

some extend however the spread of the results for the stations with higher than 35 degrees incidence angle is still visible. Moreover, the M_w estimates are slightly higher than catalog value, when the F_c and R_c are applied. Instability of the results for higher angles may be also caused by the site correction which is not known and the uncertainty of the nodal planes estimation. The angle is a trade-off between the visible bigger discrepancy of the estimates for higher angles and the availability of the stations. It would be safer to use stations up to 20 degrees as it can be indicated on Fig. 6, but there may happen situations with small number of stations fulfilling this condition for shallow events. The 30 degrees incident angle is observed for stations approximately 100 km from the source. For bigger angles and more distant stations the M_w estimates vary much more due to the wave propagation effects in shallow layers.

3. Results

The main requirement of the early warning system is the speed of the accurate estimations, the spectral method needs to be calibrated empirically. Direct measurements of the spectral level from the records are reasonably fast and accurate, but the relation (4) between M_0 and spectral level Ω_0 depends on site correction (S_c), free surface effect (R_c) and P-wave radiation coefficients (F_c), which are unknown and determination of them is not straightforward (e.g. Gibowicz and Kijko 1994). A general observation is that there are far more events with the magnitudes range from 3.6 to 4.4 (about 90% of the available data, Table 1), while the higher magnitudes are sparse, which complicates evaluation of the method aimed mostly on M5 and bigger.

Upon the tectonic features and the fact that the intermediate depth events were the most dangerous

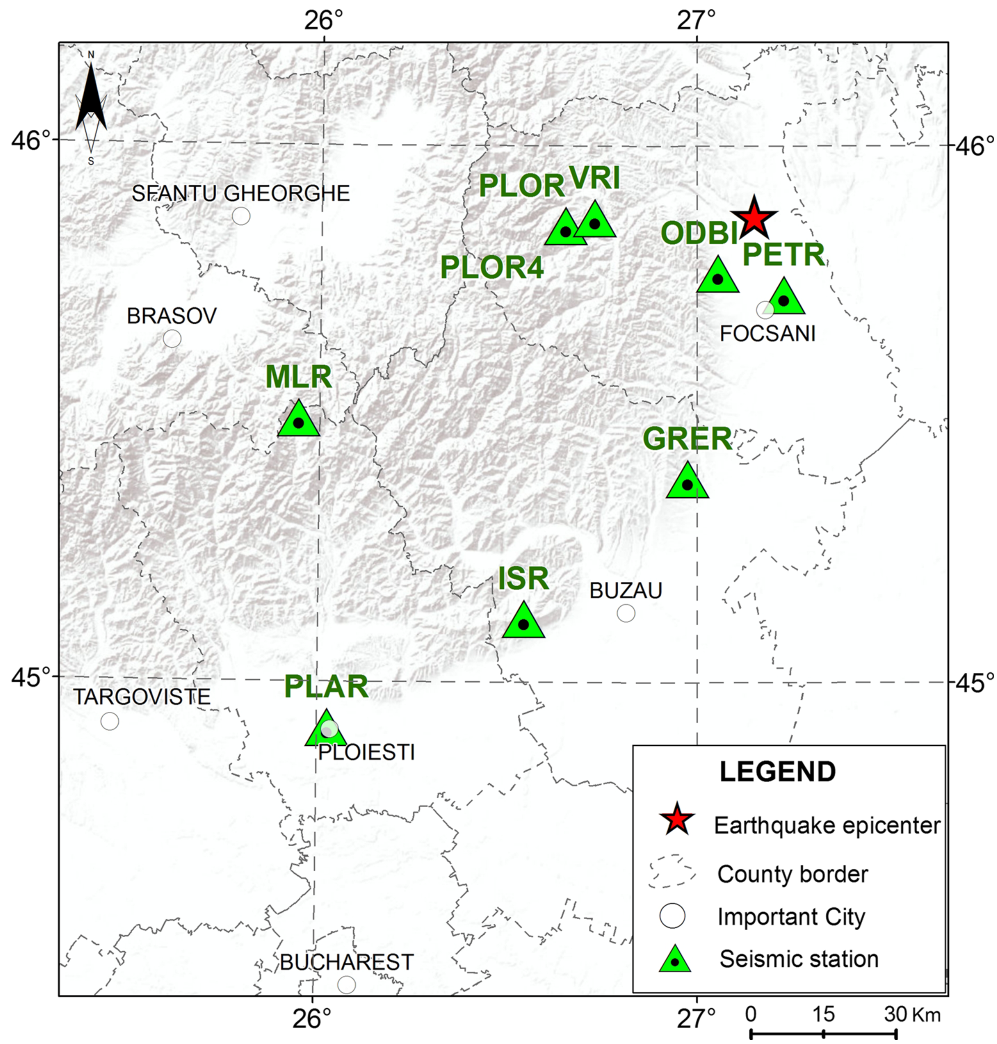

Figure 7
The M_w 5.6 event on 22 November 2014 and the stations used for fast M_w estimates

Table 1

Basic statistic parameters of the results

Estimation results	M3.6	M3.7	M3.8	M3.9	M4.0	M4.1	M4.2	M4.3	M4.4	M4.7	M4.8	M4.9	M5.4
No. of samples	2	7	12	12	13	18	8	15	2	1	1	1	1
Min	4.0	3.8	3.6	3.6	3.8	3.7	3.9	4.0	4.1	–	–	–	–
Max	4.1	4.6	4.5	4.7	4.6	4.6	4.6	4.5	4.2	–	–	–	–
Mean	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.3	4.1	4.5	4.8	5.0	5.3
Median	4.1	4.2	4.1	4.2	4.2	4.2	4.3	4.3	4.1	4.5	4.8	5.0	5.3
Std	0.1	0.4	0.4	0.5	0.4	0.5	0.3	0.3	0.1	–	–	–	–
Estimation discrepancy	0.5	0.4	0.3	0.3	0.2	0.1	0	0	−0.3	−0.2	0	0.1	−0.1

events for Bucharest only events with depth over 80 km were used for the calculations with assumption of the reverse mechanism with nodal planes similar to 1977 according to Oncescu and Bonjer (1997). Similar nodal plane orientation ($\pm$15 deg strike/dip/rake) was reported for all M6.9 and bigger events since 1940. Upon these assumption we calculated mean M_w estimates with use of all available stations with incidence angles lower than 30 degrees for the 93 events. Results are in Table 1. We can observe some overestimation up to M4.1, but in terms of estimation bigger events from M4.7 to M5.3 are mostly well estimated with up to 0.2 magnitude unit underestimation. The overestimation of weaker events may be due to different radiation pattern of some of them due to different focal mechanism.

Knowing that R_c and F_c are generally dependent from the angle of the incidence of P-waves and the focal mechanism, respectively, which may differ from case to case, the most robust way of the M_w estimations is the use of the stations, which are the closest to the source area and recorded at least several earthquakes (Table 2). This approach will allow to compare the fast M_w estimates according to the known values of the event magnitudes from the Romanian catalog Romplus (http://www1.infp.ro/arhiva-in-timp-real), where M_w is computed routinely from duration magnitude M_D (Oncescu et al. 1999). The M_w estimates were not corrected for the unknown coefficients except for using the average Fc for P-waves according to the reverse faulting focal mechanism similar to the 1977, M7.4 event. P-wave radiation coefficient Fc was calculated upon radiation pattern (Ou 2008), which is dependent from take-off angle, azimuth and nodal plane.

Table 2

Stations chosen for the fast M_w estimation

Station	Number of events
GRER	30
ISR	12
MLR	47
ODBI	37
PETR	40
PLAR	12
PLOR	67
PLOR1	61
PLOR4	57
VRI	57

Only two of chosen stations are characterized with small number of events located closely to them. Eight out of ten chosen stations recorded more than 30 events in hypocentral distance smaller than 150 km. Therefore, those stations should be the most suitable for the early warning routine due to the better statistics of the events used in calibration coefficients.

The waveforms of three events of different size and depths were used as a test of efficiency and accuracy of the proposed fast M_w estimation approach. We used waveforms of the 22nd November 2014, 39 km depth M_w 5.6 (EMSC 2014), M5.7 (NIEP 2014), 17th October 2004, 105 km depth, M_w 6 and 1st May 2011, 146 km depth M_w 4.9 events. Focal mechanism determined for the first event was normal fault with one of nodal planes: 134°/76°/−86° (Craiu et al. 2016b). In the last several years the events with M5 and bigger occurred in the shallow part. They are not so dangerous for the Bucharest, but may be dangerous for the closer settlements in the epicentral area. This was the reason of choosing this event for the test of the method. For nine available stations listed in Table 2, only station PLOR1 was unavailable (Fig. 7). The event hypocenter coordinates were 45.87N, 27.16E and 39 km depth. It was relatively shallow event for this area, which causes that the number of stations with steep incidence angle was limited, therefore the choice upon the distance criterion of the nearest stations was the most reasonable. The results are presented in Table 3. The raw M_w is estimation using only the spectral level estimated from the waveforms without any radiation and site correction coefficients, the estimated M_w is calculated with radiation pattern coefficients according to the dominant focal mechanism of intermediate depth events similar to the 1977 M7.4 earthquake used as the average mechanism for all events in this study. Then according to the take-off angle distance and azimuth the F_c upon known focal mechanism was calculated to compare the raw estimates and average ones with the results calculated with radiation pattern resulting from the event focal mechanism taken into account (Table 3).

Table 3

Fast Mw estimates of the M5.6 event (depth 39 km) on 22 November 2014

Station	Distance (km)	Radiation pattern coefficient	Raw M_w	Estimated M_w	Radiation pattern corrected M_w
GRER	69	0.59	5.5	6.0	5.6
ISR	104	0.26	5.3	5.9	5.5
MLR	111	0.31	5.8	6.2	6.0
ODBI	42	0.92	5.5	5.7	5.4
PETR	43	0.66	5.0	5.4	5.0
PLAR	144	0.05	5.3	6.2	6.0
PLOR	56	0.8	5.4	5.5	5.3
PLOR4	56	0.8	5.4	5.5	5.3
VRI	52	0.83	5.5	5.6	5.4
Average			5.4	5.8	5.5
Average without two outliers			5.4	5.8	5.5
Average without minimum outlier			5.5	5.8	5.6

The test results show, that the overestimation of the magnitude may cause some issues in case of the shallow events, when the intermediate depth focal mechanism is assumed. The shallow event estimates of M_w are overestimated on most stations as well as in average (M_w5.8), the range of M_w values is from 5.4 to 6.2, however estimates corrected with "proper" radiation pattern are less scattered (from 5.3 to 6.0) and the average M_w is 5.5. Raw estimates are lower than the averagely and properly radiation pattern corrected values. The average of raw M_w estimates for the tested event is 5.4, while the average of the estimates without minimum outlier is 5.5 (Table 3). Obviously, the estimates taking into account radiation pattern are better, but the estimates taking into account average focal mechanism of intermediate depth events are tend to overestimate the M_w of about 0.2 magnitude unit, while the average result obtained with proper focal mechanism are smaller of 0.1, but when the minimum outlying value is rejected the average magnitude estimate is the same as the catalog value.

The 17th October 2004 M_w6 event was intermediate depth (105 km) and located at 45.83N, 26.77E. One of nodal plane has following orientation: 219°/81°/107°, which is very similar to the assumed faulting orientation in Vrancea intermediate depth zone. The results of estimations are in Table 4. There were only three stations from the chosen list operating during this time, therefore fourth station TESR located 108 km from the source was also used. The resulting M_w is underestimated of about 0.2 in average, with about 0.5 range of the estimates in both methods using the radiation pattern coefficient and 0.3 in case of raw magnitudes. The latter average M_w is underestimated of about 0.3 magnitude unit.

The second deep event estimation results for 1st of May 2011 M_w 4.9 event (depth 146 km) were also prepared (Fig. 7; Table 5). It has reverse fault mechanism with nodal planes: 151°/64°/79° and 356°/28°/112° (Craiu et al. 2016a). The raw M_w estimates are less scattered (4.6–5.0, Table 5) than in case of the shallow and M6. The estimates, which take into account radiation pattern according to focal mechanism of the event are slightly over estimated (4.9–5.3), the same in case of the average focal mechanism, but the latter are much more scattered (4.7–5.7). It confirms, that estimates using focal mechanism for radiation correction work better for both intermediate depth and shallow events than raw estimates for events of M5 and bigger, when compared with the catalog magnitude.

4. Conclusions

The fast moment magnitude from P-wave spectrum performs well in case of magnitudes above M4. However the $M < 4$ are overestimated. This P-wave spectral approach for magnitude estimation allows for

Table 4

Estimates of the M_w for the M6 event (depth 105 km) on 27 October 2004

Station	Distance (km)	Radiation pattern coefficient	Raw M_w	Estimated M_w	Radiation pattern corrected M_w
TESR	108	0.29	5.6	5.5	5.5
MLR	107	0.33	5.7	5.9	5.8
PLOR	77	0.30	5.9	6.0	6.0
VRI	76	0.32	5.6	5.8	5.7
Average			5.7	5.8	5.8
Average without two outliers			5.65	5.85	5.8
Average without minimum outlier			5.8	5.9	5.8

Table 5

Fast Mw estimates of the Mw 4.9 event (depth 146 km) on 1 May 2011

Station	Distance (km)	Radiation pattern coefficient	Raw M_w	Estimated M_w	Radiation pattern corrected M_w
GRER	141	0.67	4.6	5.1	4.9
ISR	52	0.87	4.8	5.7	5.0
MLR	40	0.95	5.0	5.0	5.2
ODBI	52	0.22	4.7	5.1	5.3
PLAR	81	0.97	4.9	5.4	5.1
PLOR	34	0.47	4.6	4.7	5.0
VRI	39	0.40	4.7	4.8	5.0
Average			4.8	5.1	5.1
Average without two outliers			4.7	5.1	5.1
Average without minimum outlier			4.8	5.2	5.1

the relatively fast additional determination of magnitude with use of the nearest stations and assumed radiation pattern of the most common reverse faulting mechanism of intermediate depth events from Vrancea. The time needed for this calculation is about 3 s longer than the standard EEW approach due to the length of the P-wave window used for calculations. However, this is still within the time required for efficient EWS application. In case of larger events, the longer window length of about 5 s should be considered and therefore, the time will be even longer, but the magnitude estimate will be more precise and stable. The method can be implemented into the EEW with use of the adopting window length. The window length should begin with 3 s and then in case of the estimates above M5 increasing to 5 s and longer if the magnitude estimates are still increasing. However, in the BREWS time is crucial and 3 s are the shortest reasonable time to be useful here. Optional recalculation after additional 2 s is from the decision-making point of view that is better than waiting longer for the first estimation, especially when it does not differ much. Time needed for the calculation is relatively short in comparison of the S-wave arrival time to the Bucharest (20–30 s after P-wave), but it is matter of seconds than minutes to make a decision according to the procedure of the dangerous tremors. The method would underestimate the magnitudes of M6 and bigger events. Unfortunately, radiation coefficient F_c in case of fast estimates is not available due to the focal mechanism dependency of it, which in case of unusual focal mechanism may provide some additional uncertainties. However, the average assumed focal mechanism of similar to 1977 M7.4 event performs well in most cases, except shallow event with different faulting, which may lead to overestimation of the magnitude of about 0.2 magnitude unit.

At least eight stations have recorded more than 30 events from the chosen 93 events used in this study. These stations are the most usable for the fast M_w estimation in EWS routine for the deep Vrancea earthquakes. In case of the shallow earthquakes the method performed good, even though assumed radiation coefficient for the intermediate depth common focal mechanism was not similar to the tested event from the 22nd November 2014 M_w 5.6. But in such shallow event case (39 km depth) the calculations should be performed with use of the closest stations and the comparison between raw estimates and the general ones should be compared to avoid unusual high estimates. In case of shallow events (depth <60 km) the use of the nearest stations for calculation of raw M_w is recommended, rather than using the radiation coefficients according to focal mechanism assumed as common for intermediate depth, which performs well in case of intermediate and deep events. The average correction taking into account the 1977 focal mechanism for radiation pattern coefficient may lead to overestimation of the magnitude for shallow events. However in case of events of intermediate depth of M6 the resulting M_w is underestimated of about 0.1–0.2. Taking this into account it seems that the average correction based on 1977 event mechanism is robust for the purpose of EWS for both: intermediate depth events and shallow ones. Nevertheless, the errors of the average M_w estimates are within range 0.2–0.5 magnitude unit, which is consistent with the results for the available data. There are two possible options to avoid this issue: one is to use the raw magnitude calculations for the shallow events, second is to exclude minimal outlier value from the estimates.

Spectral approach allows to have first M_w estimates before the S-waves hit the Bucharest. It is similar like the standard approach, but using different method. It can be used parallel to maximum peak of P-waves used in EEW in standard approach. Such double estimates may be further used in the decision-making process of the emergency state as a confirmation of properly issued alert. Fast moment magnitude estimates from P-wave spectrum introduced here is robust enough to become complementary method for the routine magnitude determination in BREWS.

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